



Implications of Extracranial Distortion in Ultra-High-Field Magnetic Resonance Imaging for Image-Guided Cranial Neurosurgery

Eduard H. Voormolen^{1,2}, Sander J.H. Diederer¹, Peter Woerdeman¹, Jan Willem Berkelbach van der Sprenkel¹, Herke Jan Noordmans³, Fredy Visser^{4,5}, Max A. Viergever², Peter Luijten⁵, Hans Hooguin⁵, Pierre A. Robe¹

■ **BACKGROUND:** Ultra-high-field magnetic resonance imaging (MRI) of the brain is attractive for image guidance during neurosurgery because of its high tissue contrast and detailed vessel visualization. However, high-field MRI is prone to distortion artifacts, which may compromise image guidance. Here we investigate intra- and extracranial distortions in 7-T MRI scans.

■ **METHODS:** Five patients with and 5 patients without skin-adhesive fiducials received magnetization-prepared T1-weighted 7-T MRI and standard 3-T MRI scans. The 7- and 3-T images were rigidly coregistered and compared. Intracranial distortions were evaluated qualitatively, whereas shifts at the skin surface and shifts of the center positions of skin-adhesive fiducials were measured quantitatively. Moreover, we present an illustrative case of an ultra-high-field image-guided skull base meningioma resection.

■ **RESULTS:** We found excellent intracranial correspondence between 3- and 7-T MRI scans. However, the average maximum skin shift was 6.8 ± 2.0 mm in group A and 5.2 ± 0.9 mm in group B. The average maximum difference between the skin-adhesive fiducial positions was 5.6 ± 3.1 mm in group B. In our tumor resection case, the meningioma blood supply could be targeted early thanks to 7-T image guidance, which made subsequent tumor removal straightforward.

■ **CONCLUSIONS:** There are no visible intracranial distortions in magnetization-prepared T1-weighted 7-T MRI cranial images. However, we found considerable extracranial shifts. These shifts render 7-T images unreliable for patient-to-image registration. We recommend performing

patient-to-image registration on a routine (computed tomography scan or 3-T magnetic resonance) image and subsequently fusing the 7-T magnetic resonance image with the routine image on the image guidance machine, until this issue is resolved.

INTRODUCTION

Ultra-high-field magnetic resonance (MR) scanners are becoming more widely available and are increasingly used in neurosurgery.^{1,3} One of the main advantages of scanning at ultra-high fields is that high-resolution images with high signal-to-noise ratios can be acquired within clinically acceptable time frames. Furthermore, image contrast between different tissue types is enhanced compared with scans acquired at lower-field strengths, for example between parenchyma and blood (allowing imaging of blood vessels in great detail)^{4,5} and between tissues of differing iron and protein content (e.g., glioma and healthy parenchyma).^{6,7} Moreover, the promising visualization options for target structures of deep brain stimulation have led to investigate its use in determining the surgical coordinates for deep brain stimulation.^{2,8-10} These characteristics theoretically could make ultra-high-field images attractive to use for neuro-navigation during neurosurgical resection of brain tumors (Figure 1).

MR images acquired using ultra-high-field scanners may however suffer from artifacts that violate the assumptions of spatial encoding, causing positional distortions that may compromise the spatial accuracy needed for image guidance.^{2,11-13} Distortions can be categorized as originating from

Key words

- 7 Tesla
- Brain tumors
- Geometric distortion
- Image guidance
- Neuronavigation
- Ultra-high-field MRI

Abbreviations and Acronyms

- CT:** Computed tomography
- MR:** Magnetic resonance
- MRI:** Magnetic resonance imaging
- TE:** Echo time

From the ¹Department of Neurosurgery, ²Image Sciences Institute, ³Department of Clinical Physics, and ⁴Department of Radiology, University Medical Center Utrecht, Utrecht; and ⁵Philips Healthcare, Best, The Netherlands

To whom correspondence should be addressed: Sander J.H. Diederer, M.D.
[E-mail: s.j.h.diederer-2@umcutrecht.nl]

Citation: World Neurosurg. (2019) 126:e250-e258.

<https://doi.org/10.1016/j.wneu.2019.02.028>

Journal homepage: www.journals.elsevier.com/world-neurosurgery

Available online: www.sciencedirect.com

1878-8750/\$ - see front matter © 2019 Elsevier Inc. All rights reserved.

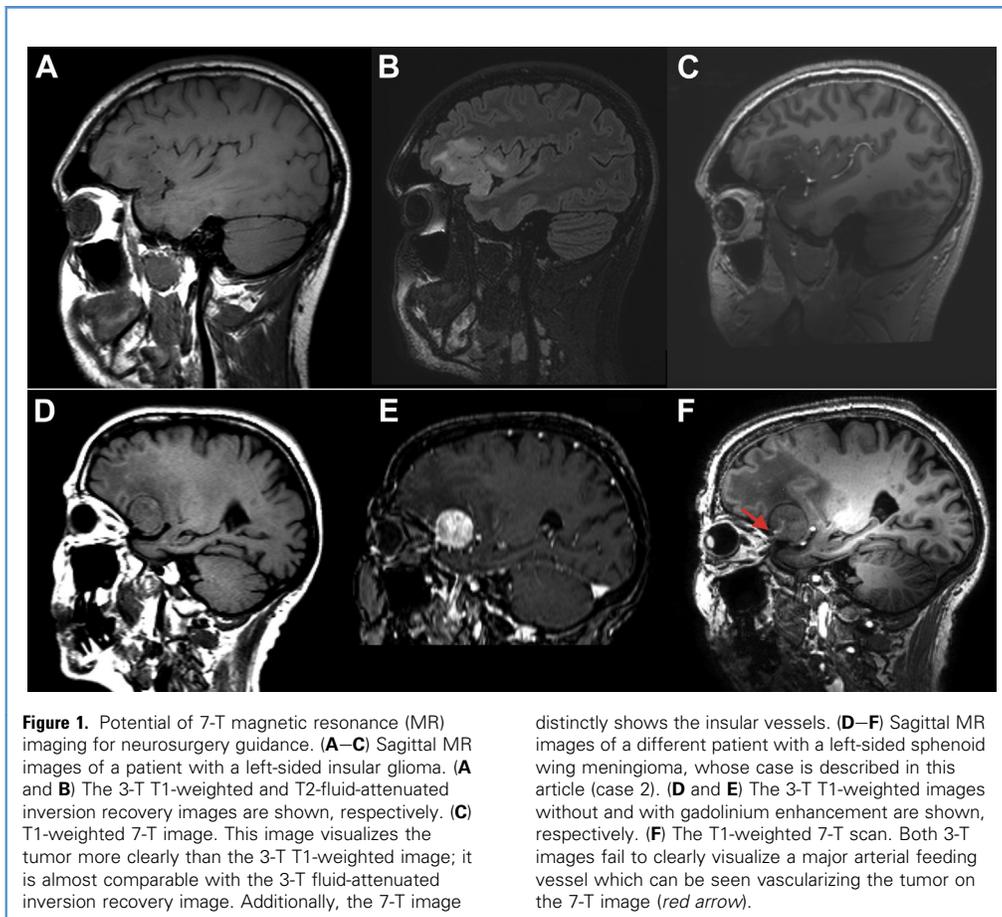


Figure 1. Potential of 7-T magnetic resonance (MR) imaging for neurosurgery guidance. (A–C) Sagittal MR images of a patient with a left-sided insular glioma. (A and B) The 3-T T1-weighted and T2-fluid-attenuated inversion recovery images are shown, respectively. (C) T1-weighted 7-T image. This image visualizes the tumor more clearly than the 3-T T1-weighted image; it is almost comparable with the 3-T fluid-attenuated inversion recovery image. Additionally, the 7-T image

distinctly shows the insular vessels. (D–F) Sagittal MR images of a different patient with a left-sided sphenoid wing meningioma, whose case is described in this article (case 2). (D and E) The 3-T T1-weighted images without and with gadolinium enhancement are shown, respectively. (F) The T1-weighted 7-T scan. Both 3-T images fail to clearly visualize a major arterial feeding vessel which can be seen vascularizing the tumor on the 7-T image (red arrow).

hardware or resulting from tissue characteristics. Intracranial distortions have been analyzed previously: hardware-related distortions in 7-T magnetic resonance imaging (MRI) are below voxel size and do not significantly contribute to inaccuracies during image-guided procedures.¹² Regarding artifacts caused by patient tissue characteristics, 7-T MR images of the brain in patients with Parkinson disease have comparable distortions with those observed on routine 1.5-T MRI.² Moreover, 7-T MR images of patients with skull base tumors have been used for image guidance previously, without being hampered by intracranial artifacts that affected clinical utility.¹⁴

Based on these reports, we attempted to use a T1-weighted 7-T MRI scan for image guidance with skin-adhesive fiducial-based patient-to-image registration in a case of glioma surgery (see [Box 1](#) for a full case description). This procedure was performed with a backup 3-T MRI-based image guidance system. To our surprise and in contrast with the aforementioned reports, tracking inaccuracies during image guidance rendered the 7-T data useless.

This led us to investigate both extra- and intracranial positional distortions at ultra-high MRI field strengths. We report here on the measured shifts in the positions of extra- and intracranial elements on 7-T MRI scans compared with standard 3-T MRI scans, and assess whether the presence of skin-adhesive fiducial markers influences these distortions.

MATERIALS AND METHODS

Subjects

To assess intracranial distortion, shifts at the skin surface, and shifts in center positions of skin-adhesive fiducials, MRI data from 10 subjects were used. Five patients without skin-adhesive fiducials were assigned to group A, and 5 patients with a total of 33 skin-adhesive fiducials were assigned to group B. Furthermore, we present a surgical case with a left lateral sphenoid wing meningioma, who was operated using 2 image guidance systems: one loaded with 3-T MR images, used to perform the procedure, and one loaded with 7-T MR images, for investigative use ([Box 2](#)). All subjects received both magnetization-prepared T1-weighted 7-T MRI and standard 3-T MRI scans.

The scans of the patients in group A were obtained from an anonymized research database (prospectively gathered at our institution). These 5 patients were diagnosed with World Health Organization grade II gliomas. Demographics for the 5 consecutive patients with skin-adhesive fiducials in group B can be found in [Table 1](#). Approval for this study was obtained from the institutional review board at the University Medical Center Utrecht.

MRI Scan Parameters. Patients received either a gadolinium-enhanced or a noncontrast T1-weighted 3-T MRI scan and a

Box 1. Case 1: Suboptimal Experience with Ultra-High-Field Magnetic Resonance Image Guidance

A 65-year-old woman presented with a 6-week history of dysphasia and progressive cognitive decline. Imaging studies found a left parietal mass with ring enhancement suspect of a high-grade intra-axial tumor. She underwent an ultra-high-field magnetic resonance imaging (MRI). An awake resection (in park bench position) with bipolar cortical stimulation was performed with the aid of image guidance with standard contrast-enhanced T₁-weighted 3-T MRI and T₁-weighted noncontrast 7-T MRI running simultaneously on 2 separate image guidance machines. The 3-T MRI fiducial registration error and 7-T fiducial registration error were, respectively, 1.9 and 3.5 mm. During surgery, we found the target registration error in the ultra-high-field magnetic resonance image guidance to be much >3.5 mm. Therefore, image guidance with the 7-T MRI was deemed unreliable and was discontinued. Maximal safe resection was achieved under 3-T image guidance and neuromonitoring, and pathologic review revealed a glioblastoma multiforme World Health Organization grade IV. There were no postoperative complications.

noncontrast T₁-weighted 7-T MRI scan. In group A, the 3- and 7-T MRI scans were obtained within 4 weeks from each other. In group B, both scans were obtained on the same day. Scan parameters were identical in groups A and B. Parameters for the 3-dimensional sagittal magnetization-prepared turbo field echo 3-T scan are as follows: field of view 256 × 256 × 192 mm³ (matrix 256 × 256 × 192), inversion time 960 ms, echo train length 232, readout repetition time 7.93 ms, echo time (TE) 4.5 ms, bandwidth 241 Hz/pixel, and flip angle 8°. The 7-T scan parameters of the 3-dimensional sagittal magnetization-prepared turbo field echo sequence are as follows: field of view 256 × 256 × 200 mm³ (matrix 256 × 256 × 200), inversion time 1200 ms, echo train length 256, readout repetition time 9 ms, TE 2.0 ms, bandwidth 506.3 Hz/pixel, and flip angle 8°. Total imaging times were 6 minutes and 44 seconds and 9 minutes and 36 seconds for the 3- and 7-T MRI scans, respectively. Prior to the acquisition at 7 T, a B₀ field map was acquired. The area of the brain of this map was used for third-order B₀ shimming. Image-based shimming was based on the acquisition of a dual echo gradient echo sequence with ΔTE = 1 ms. The B₀ maps provided by this sequence were automatically exported for further processing in an in-house developed software package. Processing consisted of brain extraction, phase unwrapping, and up to third-order fitting of spherical harmonics to the B₀ maps. The calculated shim currents were automatically loaded by the scanner software and used in subsequent sequences. At 3 T, the standard autoshim method of the scanner was used for linear shimming.

3- and 7-T MRI Coregistration. Image-to-image coregistration was performed using a 2-step semi-automated method implemented in

the MevisLab visual programming environment (MeVisLab 2.6 [MeVis Research, Bremen, Germany]). The first step was a manual 6 degrees of freedom linear registration without scaling to produce a coarse alignment of the images. The second step was an automatic linear transformation of the regions of interest based on a mutual information cost optimization. The automatic registration step was performed with the use of open source toolbox Elastix (Utrecht, the Netherlands).⁴⁵ In this fashion, the ultra-high-field images were rigidly transformed (i.e., transformation without scaling or deformation) and overlaid on the 3-T images for each subject.

Intracranial Distortion Evaluation. Qualitative evaluation of image distortion of intracranial tissue was performed on the coregistered 3- and 7-T MR images by 2 neurosurgeons (E. H. V. and P. A. R.). Two different methods were used.

First, color-coded difference images were generated based on image intensities from both images. Second, checkerboard views were made and the overlap of the images was estimated in 3 orthogonal directions (Figure 2). Both methods were used simultaneously. The difference image was used to screen for potential regions of distortion (it has a very high sensitivity for differences between images), and all these regions were then meticulously evaluated with the checkerboard view, making use of windowing, panning, and zooming and varying the size of the checked squares. We made sure that differences in the images did not represent differences in biological information (e.g., blood vessels). Different brain regions (ventricles, brain lobe cortices, and brain tumors) were evaluated systematically, and the extents of nonoverlap (i.e., distortions) were noted (Table 1). Moreover, we validated our results by comparing a 7-T

Box 2. Case 2: Benefit of Ultra-High-Field (7-T) Magnetic Resonance Image Guidance

A 74-year-old woman presented with a 4-year history of progressive short-term memory problems and a 6-month history of progressive headaches. Imaging studies revealed a solid enhancing tumor at the left lateral sphenoid wing, suspect for meningioma. It was decided to perform a resection. The patient underwent an ultra-high-field magnetic resonance imaging (MRI). Before surgery, the T₁-weighted 7-T MRI was fused with a standard 3-T MRI on the navigation machine. Because there was no gadolinium enhancement of tumor tissue, but vessels were readily visualized on the 7-T MRI, we could easily localize the major arterial feeder, a branch of the middle meningeal artery (Figure 1E). After patient-to-image registration, the fiducial registration error measured 2.3 mm. We used image guidance to direct our craniotomy and guide the subsequent drilling of the sphenoid wing to explore the feeding branch first. It was localized (Figure 5) and cauterized. Afterward, an en bloc resection of the tumor was achieved with minimal blood loss. There was no postoperative complication. Pathology showed a meningioma World Health Organization grade I.

Table 1. Demographics and Results of the Intra- and Extracranial Distortion Evaluation per Group and per Case

Case Number	Sex	Age (Years)	Group	Pathology	Location				Fiducial Shift (mm)		Skin Shift (mm)		Shift at (Number of Voxels)							
					Lobe	Side	Gadolinium	Fiducials	Mean ± SD	Maximum	Mean ± SD	Maximum	Midbrain/Ventricles	Frontal Cortex	Parietal Cortex	Temporal Cortex	Occipital Cortex	Posterior Fossa	Tumor	
1	n/a	n/a	A	Low-grade glioma	Occipital	L	No	No	n/a	n/a	1.5 ± 1.0	4,6	0	0	0	0	0	0	1	0
2	n/a	n/a	A	Low-grade glioma	Temporal	L	No	No	n/a	n/a	1.7 ± 1.2	8,8	0	0	0	0	0	0	1	0
3	n/a	n/a	A	Low-grade glioma	Insula	L	No	No	n/a	n/a	2.1 ± 1.3	9,1	0	0	0	0	0	0	0	0
4	n/a	n/a	A	Low-grade glioma	Temporal	R	No	No	n/a	n/a	1.1 ± 0.9	5,2	0	0	0	0	0	0	0	0
5	n/a	n/a	A	Low-grade glioma	Occipital	L	No	No	n/a	n/a	1.2 ± 1.0	6,5	0	0	0	0	0	0	0	0
Group mean									n/a	n/a	1.5 ± 1.1	6,8								
6	F	82	B	Neurocognitive	N/A	n/a	No	Yes	2.7 ± 1.5	4,5	1.1 ± 0.7	5,2	0	0	0	0	0	0	0	n/a
7	F	75	B	Neurocognitive	N/A	n/a	No	Yes	1.5 ± 0,7	2,5	1.0 ± 0,5	3,9	0	0	0	0	0	0	0	n/a
8	F	74	B	Meningioma	Sphenoid	L	Yes	Yes	5.2 ± 2.7	8,4	1.6 ± 1.0	6,1	0	0	0	0	0	0	0	0
9	M	25	B	Low-grade glioma	Insula	L	Yes	Yes	3.6 ± 3.2	9,4	1.1 ± 0.7	6,0	0	0	0	0	0	0	0	0
10	F	65	B	High-grade glioma	Parietal	L	Yes	Yes	3.0 ± 0.5	3,5	1.8 ± 0.7	4,9	0	0	0	0	0	0	0	0
Group mean									3.2 ± 1.7	5,6	1.3 ± 0.7	5,2								
Overall mean											1.4 ± 0.9	6,1								

n/a, not applicable; L, left; R, right; F, female; M, male.

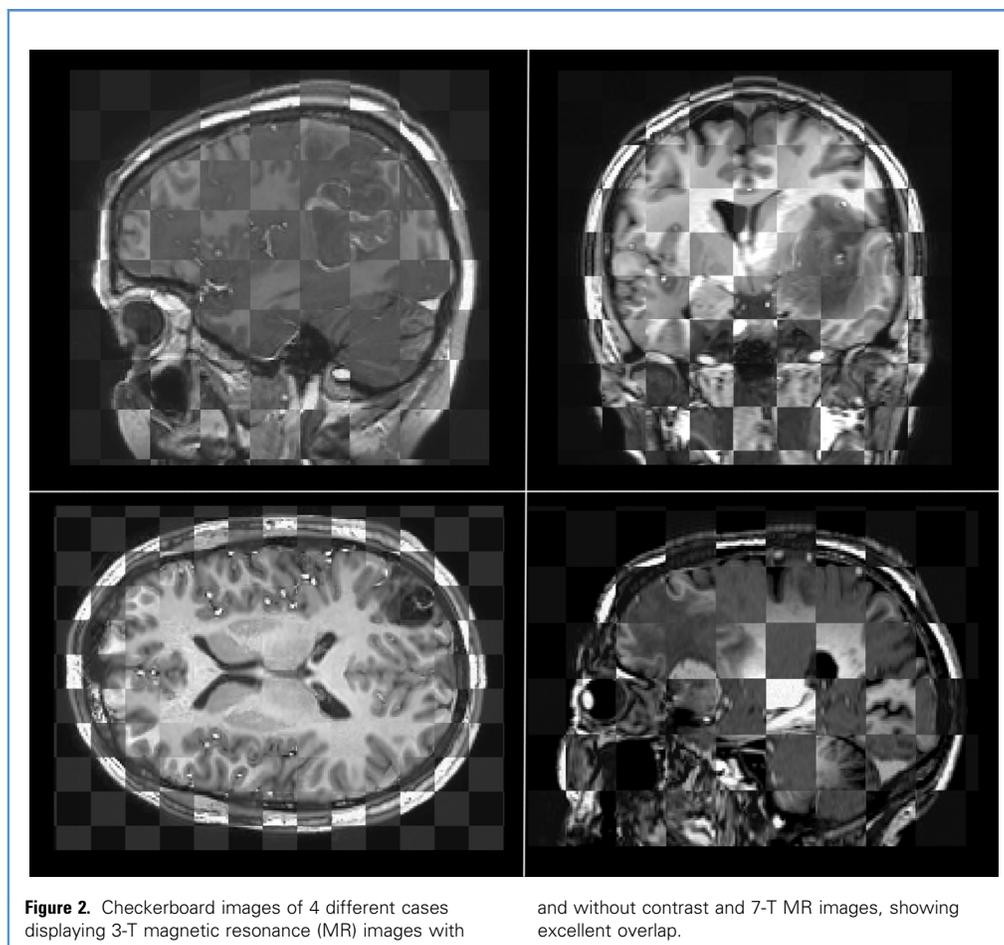


Figure 2. Checkerboard images of 4 different cases displaying 3-T magnetic resonance (MR) images with

and without contrast and 7-T MR images, showing excellent overlap.

MR image with a computed tomography (CT) image by rigidly registering both images and comparing the midcenter brain.

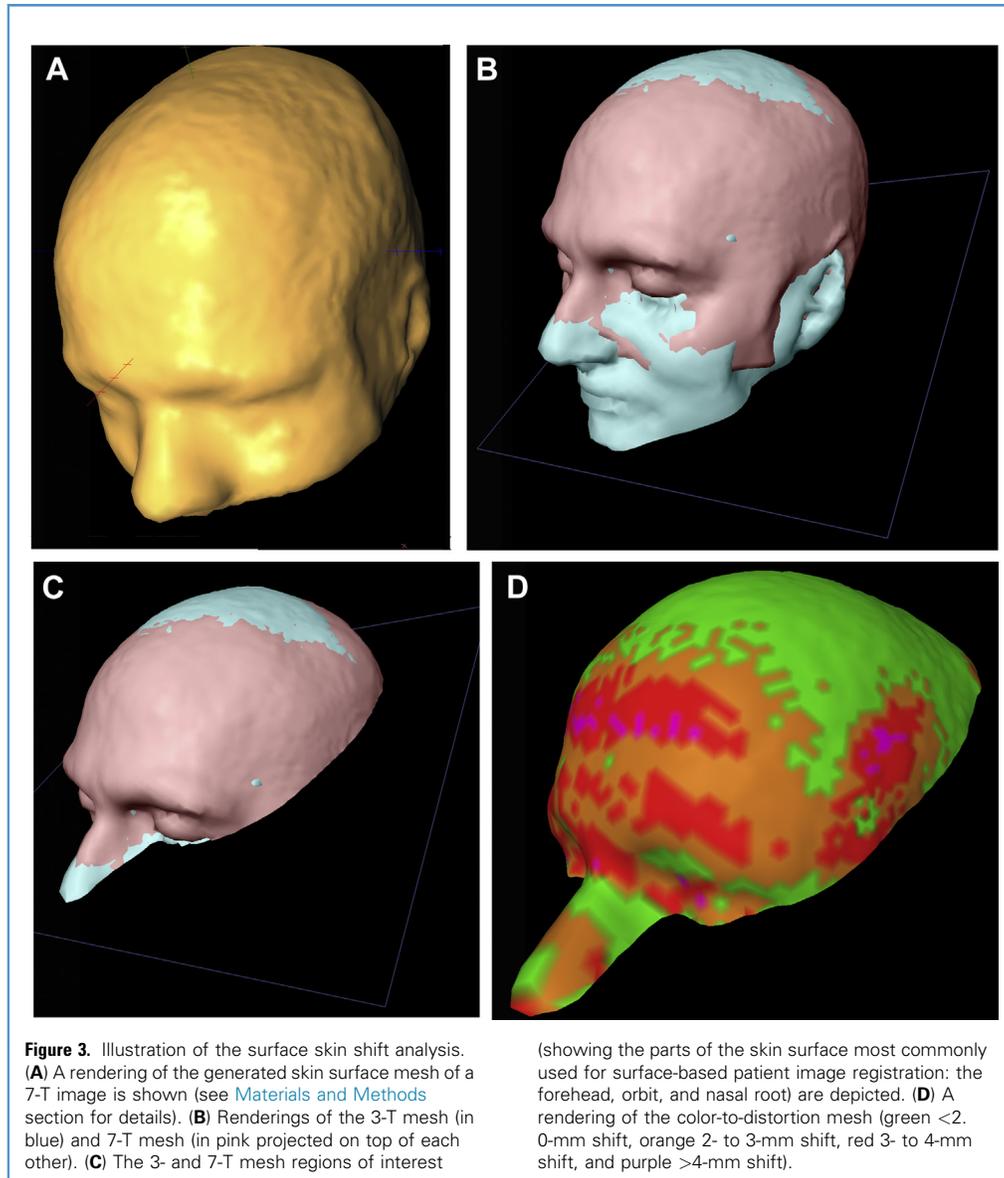
Shifts in Skin Surface. The 3-T and coregistered 7-T images were analyzed using the same BrainVoyager (Brainvoyager 20.6 [Brain Innovations, Maastricht, The Netherlands]) workflow. The built-in region-growing algorithm (threshold at the image intensity of the skin) was used to segment the cranium from the background. Background voxels were set to 0. A mesh was iteratively morphed to find the surface of the cranium with the following parameters: smoothing force of 0.07, border control of 1.0, and surface finding force of 0.3, finding intensity of the lowest image intensity of the skin; interpolation was set to trilinear (Figure 3A). The meshes were then imported into the MeVisLab programming environment and analyzed further (Figure 3B).

A region of interest was imposed on the mesh, containing the convexity of the head, orbit, and nasal root, because this area is used as matching surface for most surface-based (i.e., skin tracing) patient-to-image registration algorithms (Figure 3C). Next, the unsigned Euclidian distance between 3- and 7-T meshes was calculated for every node in the region of interest, and statistics (mean, SD, and maximum) were given. A color-to-distance-coded mesh was generated (Figure 3D). We validated this method on

additional data by comparing 3-T MR images with CT images: skin shifts yielded maxima of <2.0 mm (data not shown).

Shift in Skin-Adhesive Fiducials. The center points of all skin-adhesive fiducial markers (Medtronic, Minneapolis, Minnesota, USA) were designated by a neurosurgeon (E. H. V.) both on 3- and 7-T MRI scans of 5 patients before coregistration. We did not correct for intraobserver fiducial localization because its variability showed a submillimetric effect on target position (data not shown), as shown in previous research.¹⁶ After coregistration, the center points were subjected to the same transformation function as the images. Subsequently, the Euclidian distance between the 3- and 7-T positions for each center point was calculated in a custom-implemented method in the MeVisLab programming environment. A flowchart illustrating the analysis performed in this paper can be seen in Figure 4.

Surgical Cases. Intraoperative image guidance was performed with a Medtronic Stealth Treon system (Medtronic Surgical Navigation, Louisville, Colorado, USA). Surgeries were performed according to hospital protocol and standard microsurgical techniques. A Mayfield head clamp (Integra LifeSciences, Saint-Priest, France) was used for fixation of the head in all cases, and in the meningioma case a Budde Halo retractor system (Integra LifeSciences) was used.



RESULTS

Intracranial Distortion Evaluation

No intracranial supravoxel distortions were found in the 7-T MRI scans of group B ([Table 1](#)). We found no intracranial distortions around the brain tumors. In group A, there were 2 cases where the medulla oblongata appeared to be shifted by 1 voxel in the 7-T MRI scan compared with the 3-T MRI scan. A rigidly registered CT scan and 7-T MRI scan of 1 patient showed a midcenter brain shift of 0.81 mm.

Skin Shift Evaluation

The overall mean shift of skin surface in group A was 1.5 ± 1.1 mm, and the maximum ranged between 4.6 and 9.1 mm. In group B, the overall mean shift was 1.3 ± 0.7 mm, and the maximum shift ranged

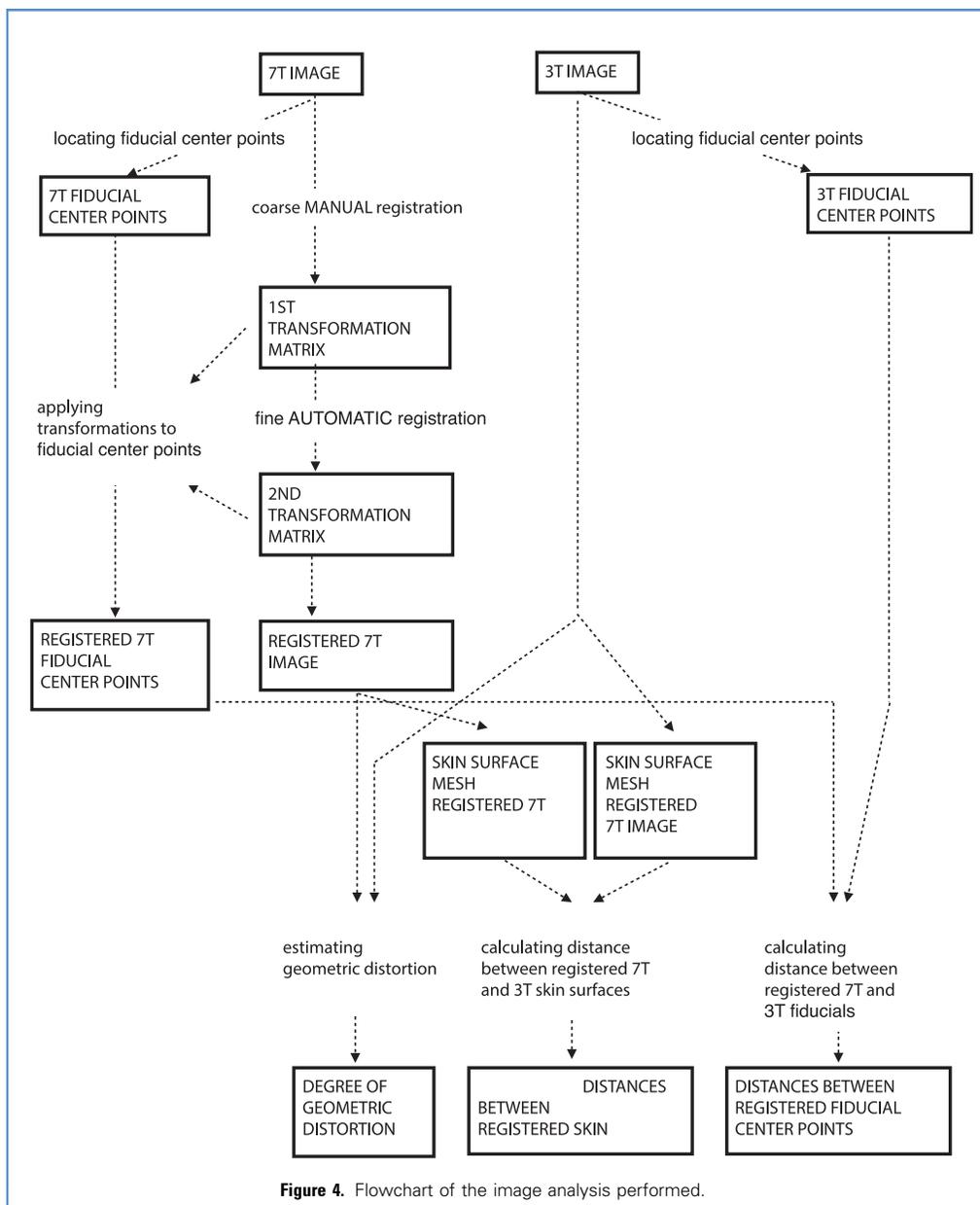
between 3.9 and 6.1 mm. Group differences were not statistically significant. The skin shift averaged over both groups was 1.4 ± 0.9 mm with an average maximum shift of 6.1 ± 1.6 mm ([Table 1](#)).

Shift in Skin-Adhesive Fiducials

We analyzed the shift in skin-adhesive fiducials in group B over a total of 33 fiducials. The average shift was 3.2 ± 1.7 mm, and the maximum shift range was 2.5 ± 9.4 mm. See [Table 1](#) for results per case.

DISCUSSION

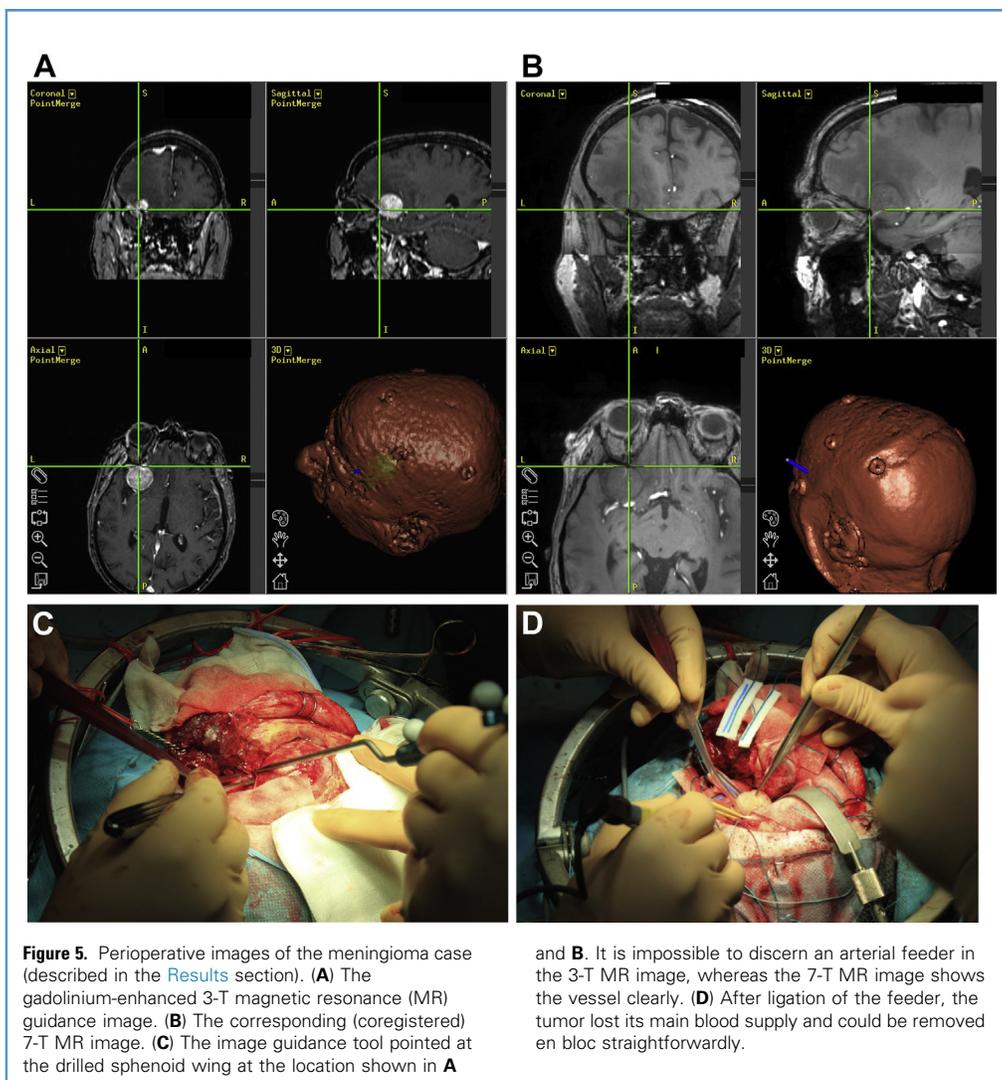
This study indicates that ultra-high-field MRI can be used safely for cranial image guidance during brain tumor resection, provided the image is not used as a basis for patient-to-image registration. The reason that we conducted this study was because we found



7-T MRI to yield major neuronavigation inaccuracies in our glioma case (as described in [Box 1](#)), whereas prior studies reassured us that geometric distortions in 7-T MRI should be minimal,^{2,12} and 7-T images could be used for image guidance.¹

We hypothesized that the observed inaccuracy was because of the skin-adhesive fiducials of our patient. Perhaps the fatty substance in the fiducials caused significant geometric distortions caused by the high magnetic field. Therefore, we investigated whether significant intra- and extracranial (skin) shifts were present in our 7-T data, and if these distortions were influenced by the presence of skin-adhesive fiducial markers.

We used qualitative methods to search for intracranial distortions, very similar to the way a neurosurgeon or radiation-oncologist in the clinic would evaluate images. Looking specifically at intracranial distortions, we confirm that the extent of these distortions in magnetization-prepared T₁-weighted 7-T MRI scans in neurosurgical patients with and without skin-adhesive fiducials appears to be of subvoxel magnitude in comparison with 3-T MRI scans. Because 3-T MRI is regularly used for clinical image guidance, this finding implies that ultra-high-field MRI should be similarly suited for this purpose, in keeping with previous reports.^{1,2,12,16} Because this finding held true in both patient groups (A and B), we also demonstrated that application of skin-adhesive fiducials does not significantly distort



intracranial contents locally. We however did observe slight positional shifts of the medulla oblongata in 2 patients in group A. Because these images overlapped very well for other parts of the brain, image-to-image registration inaccuracy is unlikely. Although motion artifacts caused by different head positions between scans may be the explanation for these shifts, we cannot exclude that the multiple tissue interfaces present in this area of the brain might have induced additional distortions. Therefore, caution remains warranted for the use of 7-T MR images for navigation in posterior fossa surgery.

We also observed that extracranial distortions can reach considerable amplitudes in 7-T MR images. We found shifts in the position of the skin surface of up to approximately 9 mm in 7-T MRI scans compared with 3-T MRI scans. These skin shifts were generally most profound around the lower forehead and orbit (**Figure 3D**), which are locations typically used in most surface-matching patient-to-image registration algorithms. Moreover, we observed that skin-adhesive fiducials could shift up to approximately 9 mm as well.

Generally, at the skin surface, there is a high chance that susceptibility artifacts occur because of the air-skin interface and because of the distance from the gradient center.^{13,16} However, our high scanning bandwidth of 500 Hz/voxel should make the occurrence of susceptibility artifacts less likely. Therefore, an alternative explanation for the extracranial distortions could be that we used third-order Bo shimming, which is known to cause Bo offsets at the level of the skin. Another possible factor contributing to skin distortion might be displacement of the skin during positioning of the head in the 7-T scanner, as a result of the tighter head coil. More research is needed to elucidate the specific cause of extracranial distortions, so as to arrive to a protocol suitable for image guidance.

Future research regarding the effect of different phase-encoding directions and other Bo shimming techniques seems to be essential to find a scanning technique that entails less skin shift and skin-adhesive fiducial shift, making 7-T scans reliable for patient-to-image registration. Moreover, these findings may

reduce local distortion and signal loss seen in especially inferior frontal areas, near air-filled sinuses, improving the use of 7-T scans for establishing deep brain stimulation targets.

In summary, we must conclude that it is presently not reliable to use ultra-high-field MRI for patient-to-image registration, either with skin surface matching or with skin-adhesive fiducial point-matching algorithms. However, 7-T MRI scans can still be used for image guidance as we demonstrated in case 2, by registering the images on the image guidance machine with another reliable image, such as 3-T MRI (as we did) or CT scan (as described by others^{1,2}).

CONCLUSIONS

This study demonstrates that no significant intracranial supratentorial geometric distortion is present in T1-weighted 7-T brain

MR images compared with 3-T T1-weighted scans of patients with skin-adhesive fiducials. Accordingly, it seems feasible to use such scans for intraoperative image guidance.

However, we found extracranial distortions on 7-T MRI scans in terms of skin surface shifts and shifts in center positions of skin-adhesive fiducials. These shifts can lead to unacceptably high patient-to-image registration inaccuracies if the 7-T MR image is used as a basis for registration.

Therefore, we recommend performing the patient-to-image registration on the basis of a routine (CT or 3-T MR) image, and subsequently coregistering the 7-T MR image with this routine image on the image guidance machine. This method was successfully used in a skull base meningioma case, where the ability to navigate on ultra-high-field MRI aided tumor resection.

REFERENCES

- Barrett T, Dyvorne H, Padormo F, et al. First application of 7-T magnetic resonance imaging in endoscopic endonasal surgery of skull base tumors. *World Neurosurg.* 2017;103:600-610.
- Duchin Y, Abosch A, Yacoub E, Sapiro G, Harel N. Feasibility of using ultra-high field (7 T) MRI for clinical surgical targeting. *PLoS One.* 2012; 7:e37328.
- Noebauer-Huhmann I, Szomolanyi P, Kronnerwetter C, et al. Brain tumours at 7T MRI compared to 3T—contrast effect after half and full standard contrast agent dose: initial results. *Eur Radiol.* 2014;25:106-112.
- Hartevelde AA, Cocker LJLD, Dieleman N, et al. High-resolution postcontrast time-of-flight MR angiography of intracranial perforators at 7.0 tesla. *PLoS One.* 2015;10:e0121051.
- Kang C-K, Park C-A, Lee DS, et al. Velocity measurement of microvessels using phase-contrast magnetic resonance angiography at 7 tesla MRI. *Magn Reson Med.* 2015;75:1640-1646.
- Li Y, Larson P, Chen AP, et al. Short-echo three-dimensional H-1 MR spectroscopic imaging of patients with glioma at 7 tesla for characterization of differences in metabolite levels. *J Magn Reson Imaging.* 2014;41:1332-1341.
- Zaiss M, Windschuh J, Paech D, et al. Relaxation-compensated CEST-MRI of the human brain at 7 T: unbiased insight into NOE and amide signal changes in human glioblastoma. *NeuroImage.* 2015; 112:180-188.
- Abosch A, Yacoub E, Ugurbil K, Harel N. An assessment of current brain targets for deep brain stimulation surgery with susceptibility-weighted imaging at 7 tesla. *Neurosurg.* 2010;67:1745-1756.
- Laar P, Oterdoom D, Horst G, et al. Surgical accuracy of 3-tesla versus 7-tesla magnetic resonance imaging in deep brain stimulation for Parkinson disease. *World Neurosurg.* 2016;93: 410-412.
- Planting B, Temel Y, Roebroek A, et al. Ultra-high field magnetic resonance imaging of the basal ganglia and related structures. *Front Hum Neurosci.* 2014;8:876.
- Archip N, Clatz O, Whalen S, et al. Compensation of geometric distortion effects on intraoperative magnetic resonance imaging for enhanced visualization in image-guided neurosurgery. *Oper Neurosurg.* 2008;62:209-216.
- Dammann P, Kraff O, Wrede KH, et al. Evaluation of hardware-related geometrical distortion in structural MRI at 7 tesla for image-guided applications in neurosurgery. *Acad Radiol.* 2011;18: 910-916.
- Wang H, Balter J, Cao Y. Patient-induced susceptibility effect on geometric distortion of clinical brain MRI for radiation treatment planning on a 3T scanner. *Phys Med Biol.* 2013;58:465-477.
- Klein S, Staring M, Murphy K, Viergever M, Pluim J. Elastix: a toolbox for intensity-based medical image registration. *IEEE Tran Med Imag-ing.* 2010;29:196-205.
- Woerdeman P, Willems P, Noordmans H, Berkelbach Van Der Sprenkel J. The effect of repetitive manual fiducial localization on target localization in image space. *Oper Neurosurg.* 2007;60:100-104.
- Dean D, Kamath J, Duerk J, Ganz E. Validation of object-induced MR distortion correction for frameless stereotactic neurosurgery. *IEEE Tran Med Imaging.* 1998;17:810-816.

Conflict of interest statement: This work was partly funded by the Alexandre Suerman personal grant received by Dr. Voormolen from the University Medical Center Utrecht, Utrecht, The Netherlands. The sponsor had no role in the design or conduct of this research. Dr. Visser is employed by Philips Healthcare, Best, The Netherlands, which is a manufacturer of 7.0-Tesla MRI scanners.

Received 10 October 2018; accepted 4 February 2019

Citation: *World Neurosurg.* (2019) 126:e250-e258.

<https://doi.org/10.1016/j.wneu.2019.02.028>

Journal homepage: www.journals.elsevier.com/world-neurosurgery

Available online: www.sciencedirect.com

1878-8750/\$ - see front matter © 2019 Elsevier Inc. All rights reserved.